Reprinted from
THE JOURNAL OF SOLAR ENERGY
SCIENCE AND ENGINEERING
Vol. 1, Numbers 2, 3. April-July, 1957

DESIGN OF THE QUARTERMASTER SOLAR FURNACE

By JOHN M. DAVIES and EUGENE S. COTTON

Quartermaster Research & Development Command, Natick, Massachusetts

The U.S. Army Quartermaster Research & Development Laboratories are charged with the responsibility for developing protection for men and materials against thermal radiation from nuclear and other weapons. This paper describes a large solar furnace now being erected at Natick, Massachusetts, for the purpose of producing a radiation flux sufficiently high to destroy materials and burn protected skin with exposure times shorter than one second. The concentrating element for the furnace consists of an area of spherical mirrors arranged on an approximate surface so that all of the images are superimposed at the target. Since a continuous reflecting surface is not required, identical mirrors produced by mass production methods are used with significant savings in cost.

INTRODUCTION

The U.S. Army Quartermaster Research and Development Laboratories are conducting a continuing program to develop protection for the soldier against the thermal radiation from nuclear and other weapons. Ideally, these studies require a source providing a high, uniform intensity over a large area. The sources which are available, such as high-current carbon arcs, gas-fired panels, burning magnesium, and incandescent lamps, are not adequate. In considering the improvement which might be made in sources, it seemed that a solar furnace offered the best hope of meeting the requirements.

The area should be large enough to produce realistic flaming of materials and to provide at least an approximation to one dimensional heat transfer conditions. The flux should be high enough to produce destruction of materials and burning of protected skin with exposure times of much less than one second. As a compromise, the minimum requirement was set at 60 cal/cm^2/sec over a circular area 4 in. in diameter in a vertical plane.

A solar image of this size will be formed by an array of spherical concentrating mirrors arranged on a sperical surface so that the images of all of them are superimposed at the target. This array resembles to some extent a large paraboloid such as has been used previously, but the performance is somewhat different. It does not require a continuous reflecting surface, so that identical mirrors produced by mass production methods can be used with a significant saving in cost.

GENERAL CHARACTERISTICS OF THE QM FURNACE

The general appearance of the QM furnace is similar to other large furnaces, such as at Montlouis. An artist's conception of the installation is shown in Fig. 1. An immediately obvious departure from usual design is the square shape of the concentrator array. This is not a necessary feature, but it seemed practical to fill the corners of the framework with mirrors and take advantage of the extra area, even though such mirrors are less efficient. The use of the corners increases the maximum rim angle from 23° to 32°; these mirrors may not be used in all exposures, since a small angle of convergence is desirable for much of our work.

The horizontal distance from the concentrator to the heliostat is 96 ft, which avoids shadowing of the heliostat by the other components. The concentrating area is 28 ft by 28 ft, with a central hole 8 ft by 8 ft, where the target chamber obscures the parallel beam. The heliostat frame is to be approximately 40 ft by 36 ft, with a smaller central hole to allow for the target chamber. A venetian blind-type shutter is mounted so that it can be used to attenuate the parallel light without obscuring the convergent beam. The measuring apparatus, shutters, controls, and laboratory facilities will be housed in the target chamber, which will be reached by a small elevator platform.

The effective focal length of the concentrating surface is 35.8 ft, giving a solar image of 4 in. diameter if perfectly imaged. The projected area of the concentrator perpendicular to the parallel beam is 710 sq ft. This gives a theoretical concentration factor of about 8160. Assuming a nominal furnace efficiency of 50 per cent, and an *average* solar constant at the site of 0.020 cal/cm^2/sec, we could then obtain an average of 82 cal/cm^2/sec at the center of a uniform image, which is greater than the intensity we have set as a design objective. These calculations can be made more accurate and detailed, as will be shown later. However, such order-of-magnitude constants enabled us

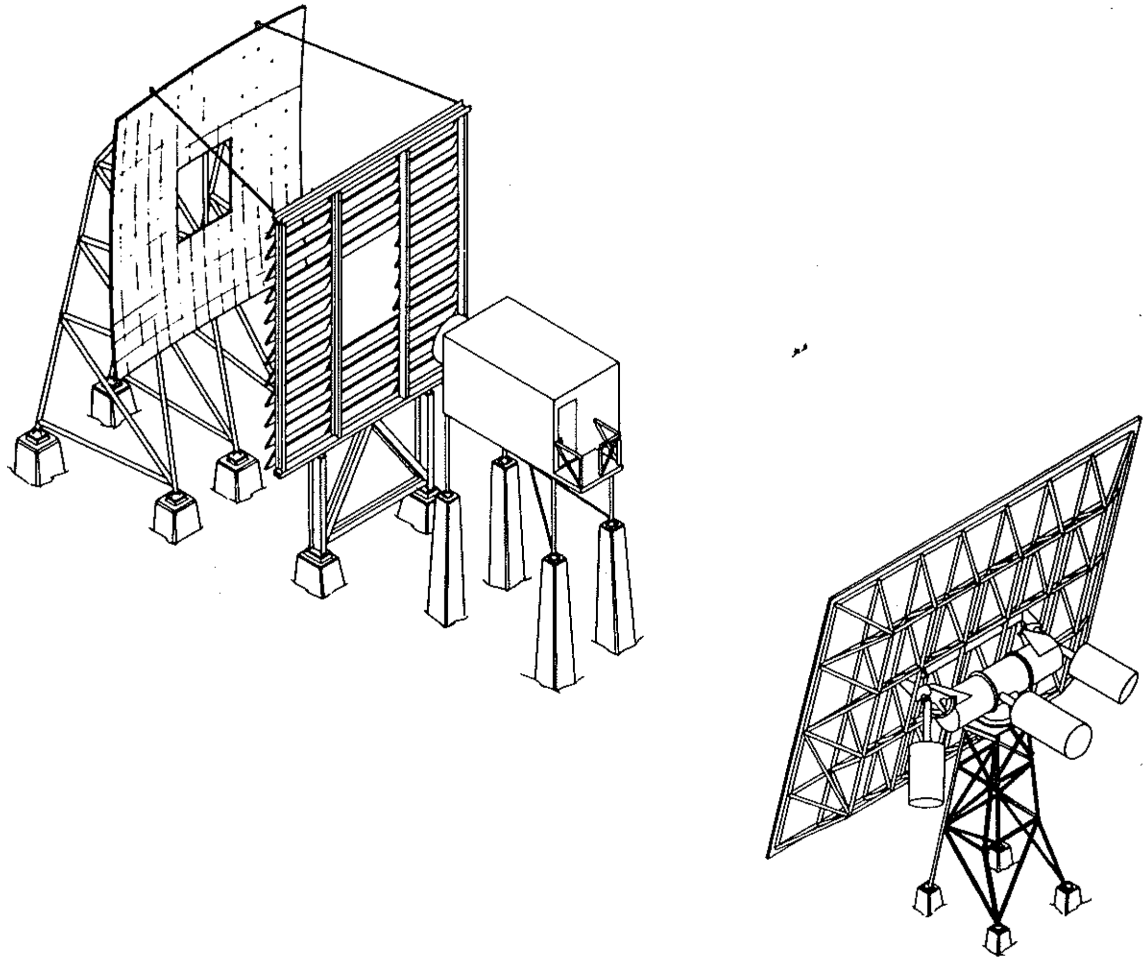


FIG. 1 — Drawing of furnace.

to arrive at practical sizes of the components. If we were to use this furnace for power applications we could expect an output power of 25-30 kilowatts under average conditions.

CONCENTRATING ARRAY

The use of an array of individual focusing mirrors was originally suggested by R. Gardon.[1] A similar concept has been employed in the MIT furnace through the use of flat mirrors.[2] Although the mirrors in the MIT instrument did not focus the light, nevertheless superposition of the beams from individual mirrors was used to form a composite beam. The objective of the MIT furnace was essentially the same as for the QM furnace, to produce a nearly uniform area of irradiation. Extrapolation of the flat mirror design to larger area and higher intensity, however, was found to be impractical owing to the large number of separate mirrors requiring alignment, and to the loss of energy from flat mirrors due to beam "spread". The use of individual focusing mirrors permits a longer effective focal length and a smaller angle of convergence. Also, the total number of individual mirrors is reduced considerably. Ideally, from such an array, all of the radiation is focused within the 4-in. diameter solar image. The area is not uniformly irradiated, however; this will be treated in a later section.

The size and shape of the individual curved mirrors are determined by quite practical considerations. It is desired that the mirrors fit closely on the array without wasting area. This condition suggests a polygon, and for the sake of simplicity in manufacture we have chosen a square, 2 ft on a side. With this choice, the number of mirrors mounted on the array is 180. Each mirror will be mounted on an aluminum ring which has a diameter of 23.5 in. The ring adds symmetrical rigidity to the mirror, and also provides a support for fastening to the framework and adjusting the angle of inclination to the incoming beam.

The early design of the concentrator was based upon a paraboloidal shape, or an approximation to it, by means of several zones with different radii of curvature. This scheme is obviously costly, regardless of the method of mirror formation. Our final design is based upon the use of individual spherical mirrors, all having the same radius of curvature, and mounted on the array in such a way that the best image from each occurs at the target position.

This arrangement was evolved through many stages, but the principal considerations were cost and optical aberration. The first is quite obvious; we aimed at a single mirror which can be mass-produced. The second consideration concerns the optical performance of the spherical mirrors, and deserves a brief explanation.

Instead of considering the concentrator as a single reflecting surface, it is viewed as an arrangement of individually focusing spherical mirrors. The mirror which is placed in the on-axis position, or at the center of the array, must focus at

$$f = \frac{d}{\alpha}$$

where d is the image diameter and α is the angle subtended by the sun. In our case, $d = 4$ in. and α is .00931 radians, which gives $f = 429.6$ in. (35.8 ft). The radius of curvature of a spherical mirror is twice its focal length, or 859.2 in.

Actually, there is no mirror at the center of the array; all of the mirrors are operated off-axis, since all of them are required to produce a solar image at a point on-axis 35.8 ft from the center of the array. Our task is to devise a surface which will make this possible for all mirrors.

The first approximation to such a surface is obtained by a consideration of the third order aberrations which apply to a spherical mirror. For an object at infinity (i.e. the sun) the image distance due to spherical aberration for an extreme ray parallel to the axis is

$$a = -\frac{R}{(2 + h^2/R^2)}$$

where R is the radius of curvature and h is the distance from the axis where the ray is incident. For a square mirror, 24 in. on a side, the maximum value of h is $12\sqrt{2}$, or about 17 in. The value of R is 859.2, so that

$$a = -\frac{859.2}{2 + (17)^2/(859.2)^2} = -\frac{859.2}{2.004} = -429.5 \text{ in.}$$

Thus, the image from the extreme rays is formed 0.1 in. closer to the mirror than that from axial rays. As will be seen, this aberration is quite small.

The coma produced in the solar image due to the lack of uniformity in lateral magnification by this mirror can be shown to be quite small. Third-order theory for a mirror results in the following formula for the radius of the comatic circle:

$$r_c = \frac{3yh^2}{4f^3}$$

where y is the distance of the image from the mirror axis. For our extreme mirror, i.e. a corner of the array, y is about 110 in., and as before, $h = 17$ in., $f = 429.6$ in.

Thus,

$$r_c = \frac{3\ (110)\ (17)^2}{4\ \ (429.6)^3} = 0.0003 \text{ in.}$$

The tangential coma is $3r_c$, or about .001 in., so that the image of a point source at infinity would become a circle of diameter .0006 in., with a .001 in. "tail" extending to the true image position. Such an aberration is completely negligible in the case we are considering.

Next we must calculate the principal aberration due to the off-axis operation of our mirrors. This effect is known as astigmatism. A point source at infinity which is not on the axis of the mirror will produce two line images which are not at the same point in space. These lines are perpendicular to one another, and are separated by a distance which depends upon the angle which the incoming beam makes with the axis. The tangential, or primary, focus for a spherical mirror is formed at a distance

$$a_t = \frac{R \cos \beta}{2}$$

from the center of the mirror, where β is the angle which the incoming beam makes with the principal axis. The sagittal, or secondary, focus is formed at

$$a_s = \frac{R}{2 \cos \beta}$$

In our case, the maximum value of the angle β is about 15°, so that

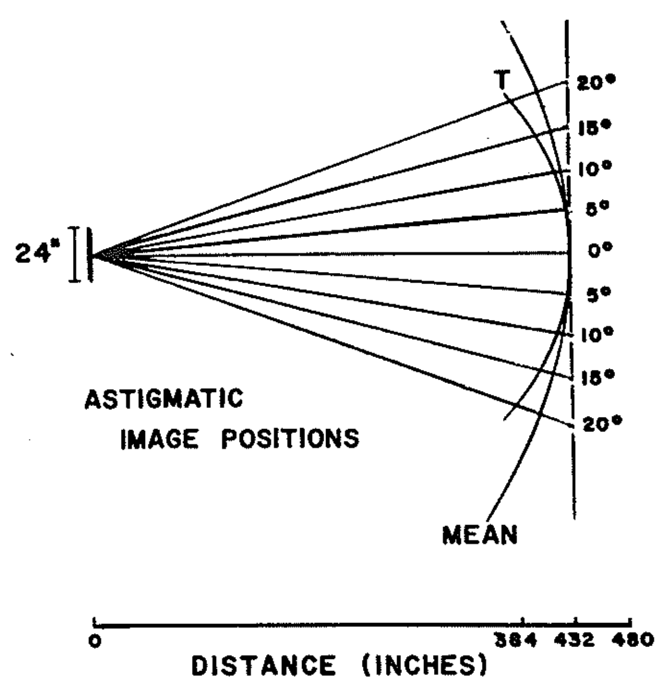
$$a_t = \frac{(859.2)\ (.966)}{2} = 415.0 \text{ in.}$$

and

$$a_s = \frac{(859.2)}{2\,(.966)} = 444.7 \text{ in.}$$

The maximum astigmatic difference is $(a_s - a_t)$, or 29.7 in. The best image is difficult to define for a system suffer-

FIG. 2 — Astigmatic image position.



ing from astigmatism; the loci of the mean positions form a nearly spherical surface about the mirror center. In our case, at $\beta = 15°$, the mean position is at 429.8 in. from the center; this differs by only 0.2 in. from $R/2$. A "mean focus" is the position where the image of a point source is spread out into a minimum illuminated area which has the approximate outline of the mirror itself. In our case, this is nearly a square; if the image is formed on a vertical plane, as in the system under study, the square image becomes a trapezoid. The effect of the astigmatic aberration for a mirror of these dimensions is shown in Fig. 2.

The other classical aberrations, distortion, and curvature of the field, do not concern us here, since the sun as an object has such a small lateral extent. Also, a mirror is not subject to chromatic aberration.

In summary, each individual mirror forms an image which is subject to two aberrations of consequence. As a result of spherical aberration, a mirror of these dimensions would form a mean image between 429.5 in. and 429.6 in. from the mirror center, if used on-axis. The operation of the same mirror 15° off-axis produces a "mean" image at about 429.8 in., also measured from the mirror center. The astigmatic difference is quite large, however, so that significant changes in image size would be detected only by moving several inches away from the mean position.

Since these estimates of mean image position were calculated using only the results of third-order aberration theory, it seemed advisable to consider higher order aberrations and also to use more exact methods. The operation of a spherical mirror of this radius at off-axis angles of 15° or less was investigated by Davis[3] using ray tracing techniques. This method reduces the number of approximations involved and treats all aberrations simultaneously. Davis found that the distance from the mirror center to the mean image position decreased very slightly with off-axis angle. The outermost mirror, according to this result, would need to be advanced from a spherical surface in the direction of the incoming beam less than 2 in.; such a correction can easily be made in adjustment of the mirror on the array. Using ray tracing, the best image is calculated by obtaining the spread of an image of a point source in the vertical plane, and minimizing the area. In third-order theory, we merely assumed that the best image occurred at the mean between the astigmatic images, and found the deviation from a spherical surface to be negligible.

These optical considerations yielded a result which defined a design criterion. If the best image position for each mirror is approximately at $R/2$, then the centers of all mirrors must lie on a surface which is part of a spheroid of radius $R/2$. The slope of the spheroidal surface is not coincident with the slope of the mirror, since its purpose is only to position the mirror for best imaging. Fig. 3 shows the shape of the surface and the approximate mirror positions in a vertical section.

It is desired that the mirrors used in this furnace be quite efficient optically, and that they preserve the solar spectrum as far as practicable. In order to achieve these

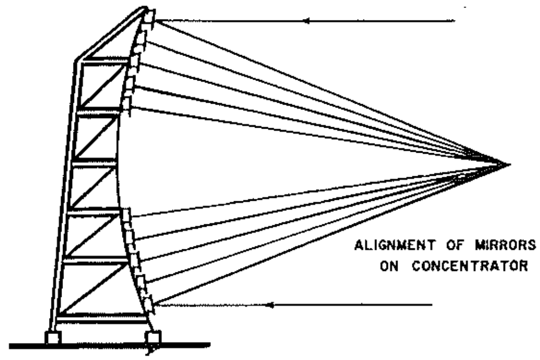


FIG. 3 — Location of mirrors on concentrator.

goals we have chosen front-surface aluminized plate glass as the concentrator mirror material. The aluminum surface will be protected by silicon monoxide. It is planned to cover the mirrors when they are not in use. The plate glass is ¼ in. thick, and the desired curvature will be produced by slumping over an accurate mold, with grinding and polishing only if necessary. A standard deviation of 2.5 per cent in the mean radius of curvature has been set as our allowable tolerance.

Each mirror will be fastened securely to the aluminum ring, which will be mounted on the array by means of three universal-type joints to provide adjustment in depth and angle. The mirrors will be aligned individually so that their images are completely coincident, probably through the use of an artificial source at the focus.

HELIOSTAT

Our need for a solar image at a fixed point on a vertical plane virtually dictated the use of an auxiliary heliostat. Heliostatic arrays of this size are not common, the largest in use being at Mont Louis.[4] The basic requirement placed upon the heliostat is that it maintain the reflected beam in a fixed position parallel to the principal axis of the concentrator. This results in a movement of the heliostat such that its normal bisects the angle between the sun and the concentrator at all times.

This constraint does not completely define the motion of the heliostat plane; it is defined, however, when the set of axes about which the plane will move is chosen. Astronomical instruments often use an equatorial type of mounting to reduce the motion so that a constant speed drive about one axis is almost sufficient. In such a mounting, one axis is perpendicular to the earth's equatorial plane and the other is parallel to it; the tracking of celestial objects is accomplished by a constant speed about the first axis, while the other is adjusted periodically for changes in the declination. Our heliostat does not track a celestial object, but is oriented toward a point moving on the celestial sphere in both azimuth and elevation. However, we calculated the motion required for an equatorial mounting to see whether any advantage could be obtained from it. The results showed that the total motion about one axis was somewhat reduced, but that an undesirable tilting of the heliostat frame with respect to the horizontal plane was encountered. This

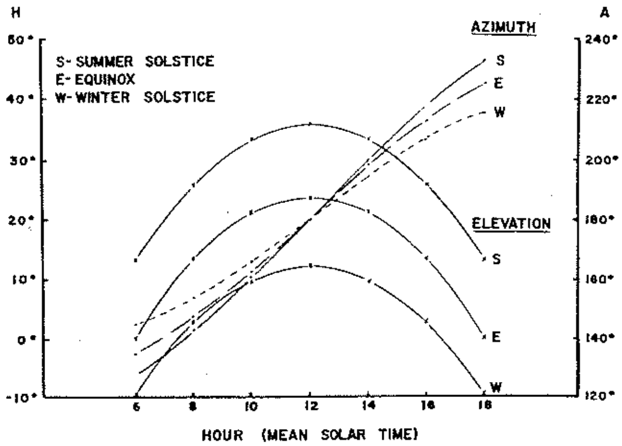


FIG. 4 — Angles of heliostat.

would require a larger mirror surface and also would force the whole array to a greater height above the ground.

Since there is no set of axes for a heliostat which permits motion to be restricted to a single rotation, a conventional azimuth-elevation mounting referred to the horizontal plane was chosen for its simplicity. The actual mounting to be used is one which has been utilized for radio telescopes and radar antennas, developed by the D. S. Kennedy Co. of Cohasset, Mass. The approximate azimuth and elevation angles which occur at various hours of the day are shown in Fig. 4. These angles were computed using a "mean sun" — the heliostat will actually track according to the apparent motion of the true sun. A sensing element which keeps the reflected beam incident upon the concentrator will position the heliostat automatically about both axes. It is hoped that we can control the position of the heliostat within ½ minute of arc, so that the motion of the image will be less than 1/16 in. away from the target position.

The over-all size of a heliostat array can be calculated by projecting the small cone of light from the sun so that it uniformly illuminates the concentrator at all positions of the heliostat. This has been done in an elegant manner by Jose,[5] using two different locations of the elevation axis in the mirror surface. The concentrator discussed in the previous section is square, so that it is not practical to provide full illumination at all usable hours. However, nearly full illumination can be provided on the longest day of the year for about 8 hours if a heliostat size of 40 ft by 36 ft is employed. This size is computed through the use of Jose's method, which assumes that the axes are in the reflecting plane. In practice, this will not be the case; engineering requirements result in an offset of the axes from the heliostat plane. Such an offset would require an increase in area if full illumination of the concentrator were needed for the entire period.

The heliostat framework will be constructed of aluminum, to which the mirrors will be attached directly. The flat mirrors will be ¼ in. polished water-white plate glass, again in the form of squares, 2 ft on a side. The reflecting surface will be the back surface of the glass, silvered and protected with copper plating and paint. Each mirror will be supported at three points on a centered circle by means of screws which are fitted into oversized holes in the glass. A spring behind each support will keep the mirror correctly positioned but will permit thermal expansion in the plane of the mirror. It is not necessary that all mirrors be exactly in the same plane, only that they remain parallel.

The heliostat will not be required to track accurately in winds exerting a force over 5 lb per sq ft, and is designed to survive winds of hurricane velocity, which sometimes occur at our location. The furnace site is at the edge of a small lake so that the western horizon for the heliostat is very low. The eastern horizon is somewhat limited by buildings and trees, so that early morning operation is restricted.

OTHER COMPONENTS

In order to secure efficient operation and use of the furnace certain auxiliary components will be needed. Our first consideration is, of course, for the safety of personnel working near the focal point. A method of shutting off the concentrator is needed in case the solar image moves or begins to damage material within the test chamber. To accomplish this we have planned a venetian shade-type attenuator (shown in Fig. 1) which will be closed automatically in case of power failure, incorrect tracking, excessive image movement, lack of cooling in shutters, and other emergencies. The operator will also be able to close the attenuator suddenly if he thinks it advisable.

Such an attenuator can obviously be used also to control the total radiation which is incident upon the concentrator. The attenuator will be placed so that it regulates the amount of parallel light from the heliostat, but does not interfere with the convergent beams from the concentrator. The blades will be electrically operated so that the operator can select the desired intensity attenuation while inside the test chamber.

The test chamber will be 8 ft by 8 ft in a cross section presented to the parallel light, and almost 16 ft in the direction of this beam. Inside the test chamber will be the sample-holding equipment, heliostat control panel, and instruments for measuring effects on samples. Also mounted inside the chamber will be a fast exposure shutter, giving exposures as short as 0.1 seconds, and a water-cooled, protective shutter which is designed to shield the exposure shutter and sample apparatus until just before the exposure is made. Shutters of this type are now in use with the QM carbon arc and have been found to be quite satisfactory. The chamber will be temperature controlled. Access will be gained by means of an elevator at the rear. The incoming parallel radiation will be monitored for available intensity at any time, and the concentrated radiation will be measured by means of copper button calorimeters.

EXPECTED PERFORMANCE

The requirement placed upon the QM furnace is the formation of a uniformly irradiated 4-in. diameter spot.

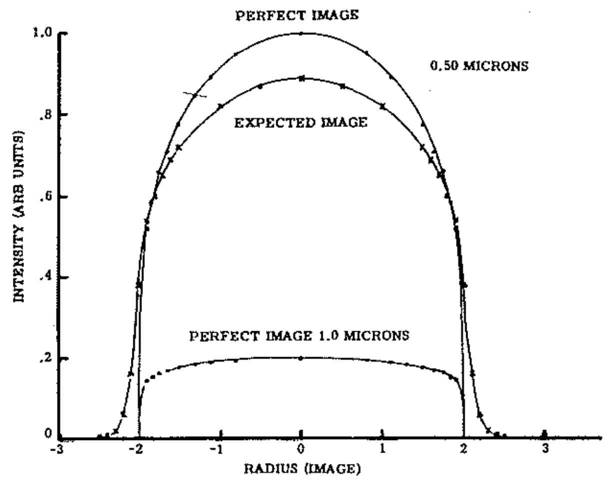


FIG. 5 — Quality of solar image.

A perfect solar image will not, of course, have this property of uniformity. The radiancy of the solar disk is shown in Fig. 5 for wave lengths of 0.5 microns and 1.0 microns.[6] No single image of the sun can be more uniform than this at the same wave length. Various arrangements for defocusing some of the elemental mirrors could be devised which would redistribute the radiation, but in any such scheme some of the radiation must be discarded from the desired image area. It is therefore felt necessary to align the furnace for the best possible composite image, measure its radiancy as a function of distance from the center, and then utilize auxiliary stops, or some other means, to make the irradiance more uniform if it is desirable.

One can arrive at an approximation to the image shape by a consideration of the astigmatic aberration discussed earlier. Each object point is imaged as an area, whose size is dependent upon the off-axis angle obtaining for that particular mirror. The methods of ray tracing[3] provide a simple way of determining the size of this area; the image from the mirror is then thought of as the sum of these areas which have a one-to-one correspondence with each point in the sun. In addition, the image from each mirror is spread into an ellipse as a result of the angle which the incoming ray makes with the vertical target plane.

For this purpose, the array surface was considered to be composed of mirrors in seven zones, each zone con- image from the mirror is then thought of as the sum of tributing a composite image of a different radius. The zonal image was then calculated using the "spread" due to the aberration and the angle of incidence on the target for that zone. The images from the seven zones were weighted according to their contribution to the total image. This expected image, shown in Fig. 5, is spread over a larger diameter, about 5.8 in.

As a result of image enlargement the intensity of the radiation at the center of the image will be reduced. We showed earlier than an average of 82 cal/cm^2/sec might be expected from the furnace using the theoretical concentration factor and an approximate estimate of furnace efficiency. This assumed a uniform image intensity; actually, at 50 per cent efficiency, the intensity near the center of a perfect image would be higher, about 106 cal/cm^2/sec. The actual image will give a central intensity of approximately 94 cal/cm^2/sec and it will fall to about 40 cal/cm^2/sec at the 2-in. radius. Thus we have already achieved a somewhat more uniform image over the 4-in. diameter, but, as expected, at the expense of radiation thrown beyond the 4-in. diameter. Further improvement of this intensity profile toward uniformity may be achieved by the judicious use of stops in the central part of the beam, at a distance where the temperature would not become excessive. These stops could be silvered to keep their temperature low, and they would simply remove radiation from the beam which was destined to contribute principally at the center of the image.

In order to present a comparative picture of this furnace, some of the essential characteristics[7,8] are tabulated in Table I.

TABLE I

CHARACTERISTICS OF THE QUARTERMASTER SOLAR FURNACE

Number of reflectors	2
Aperture	28 ft x 28 ft (square)
Focal length	35.8 ft
Ratio of aperture to focal length	0.78 - 1.11
Effective concentrating surface	710 sq ft
Theoretical diameter of image	4.0 in.
Expected diameter of image	5.8 in.
Theoretical concentration ratio	8161
Estimated over-all concentrating efficiency	50 per cent
Probable concentration ratio	4080
Average image flux density (sun at .08 watts/cm^2)	326.4 watts/cm^2
Input power	53 kilowatts
Output power (over perfect image)	27 kilowatts
Maximum flux density in expected image	94 cal/cm^2/sec

All of the performance characteristics in Table I are based on an average solar constant at sea level of .08 watts/cm^2, (or .019 cal/cm^2/sec), as used by Benveniste.[7]

CONCLUSION

The QM solar furnace is planned for initial alignment and operation during the summer of 1957. It will be the first large furnace of the focusing type to utilize an effective aperture to focal length ratio of less than one. We hope that it will furnish much valuable information on the effects of high intensity thermal radiation of materials. In addition, it may contribute to the general solar energy field by its use of front-surface mirrors, prefocused and mass-produced, on a nonparabolic array. Such experience, added to that of the many other furnaces in use and under construction, may assist in the application of solar energy concentration to the problems of dwindling sources of power on earth.

REFERENCES

1. R. Gardon, private communication, 1955.
2. R. Gardon, "A segmented-mirror solar furnace for high intensity thermal radiation studies." *Rev. Sci. Inst.* 25: 459, 1954.
3. W. Davis, private communication, Oct. 29, 1956.

4. F. Trombe, "High temperature furnaces." (In *Proceedings of the World Symposium on Applied Solar Energy, Phoenix, Arizona,* 1955, p. 63.)
5. P. D. Jose, "The design of a heliostat mirror for a solar furnace." Report No. HDR(RM)-TM-56-3, Holloman Air Force Base, July 1956.
6. C. G. Abbot, "The sun as a source of continuous radiation." (In *Sources of Radiant Energy,* ed. by W. E. Forsythe, N.Y., McGraw-Hill, 1937, p. 75.)
7. G. Benveniste, "Solar energy furnaces." Menlo Park, Stanford Research Institute, 1955.
8. G. Benveniste and N . K. Hiester, "The solar furnace—new tool for high temperature work." *Mech. Eng.* 78:915, 1956.